Laser altimetry and the cartography of Earth, Mars, Moon, Venus, and 433 Eros

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ABSTRACT
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More than 72000 ranges to the Moon, 16 million to the asteroid 433 Eros, and over 600 million to Mars have provided the cartographic context for future exploration. In the case of Mars, the accuracy of geolocated and crossover-corrected MOLA shots approaches 1 m radially and 100 m horizontally, while the Near Laser Rangefinder shots on Eros are known to about 10 m in x,y,z. Our nearest neighbor the Moon is by far the least accurately measured topographically, with 100 m radial and >1 km horizontal uncertainty, owing to the low sample density and the absence of crossovers. (While Earth's land surface is precisely measured by various means with variable accuracy, the ocean basins are poorly mapped.)

We present advances in the understanding of altimetric profiles on Mars and Eros using crossovers. In the former case, pointing knowledge of the MGS spacecraft is the limiting factor, while in the latter case, orbital knowledge of the Near-Shoemaker spacecraft is the primary source of uncertainty.

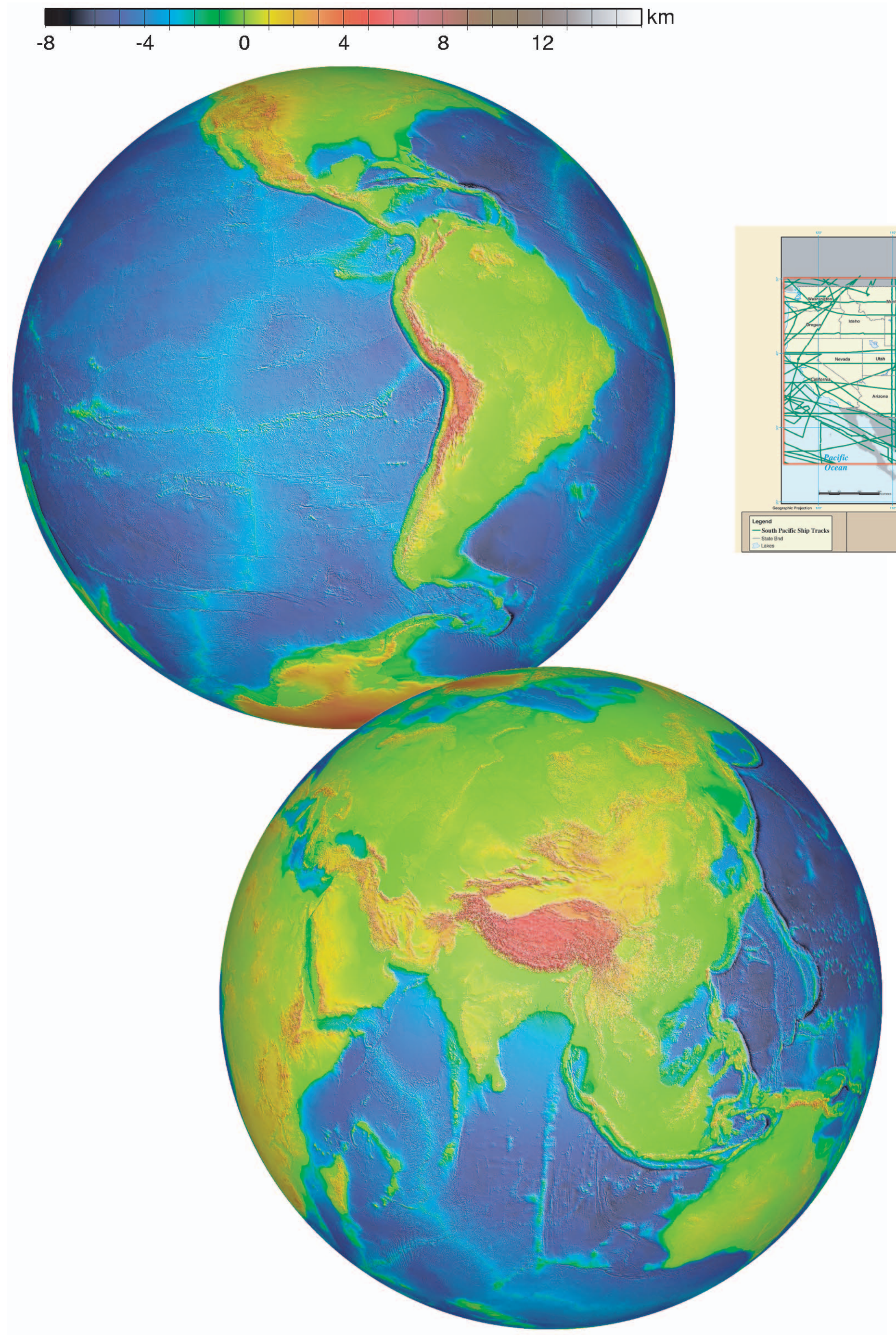
Photometry and imaging, as implemented in the MOLA instrument and the Mercury Laser Altimeter to be flown on the MESSENGER mission, provide an additional tracking constraint.

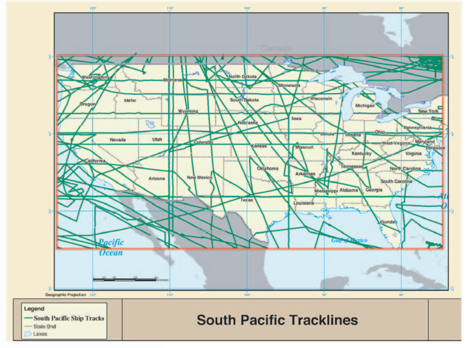
For details of this paper and ancillary data:
ftp://ltpftp.gsfc.nasa.gov/projects/tharsis/cross/
For more information about the MOLA investigation:
http://ltpwww.gsfc.nasa.gov/tharsis/mola.html

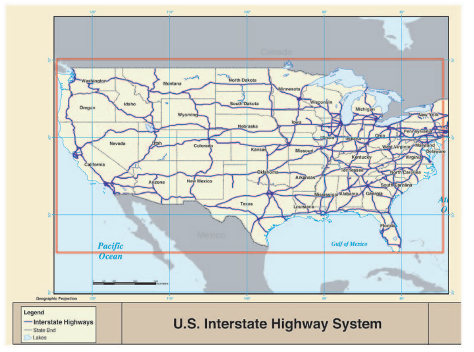
1. The shape of the Terrestrial bodies

The planetary images shown here very roughly to scale all use the same color stretch to render topography and all have comparable dynamic range despite their differences in size.

The earth is perhaps the least well-known shape of the solid bodies shown here, as bathymetry is no better sampled in some regions of the South Pacific than the Interstate Highway system in the U.S (maps courtesy of George Sharman, NGDC). Most of the bathymetry in these regions has been predicted on the basis of satellite-derived gravity fields, with a horizontal resolution of ~10 km and a vertical accuracy of 100-1000 m, depending on the density of ship tracks. The ABYSS mission, using an advanced Delay-Doppler Radar Altimeter, would improve our knowledge of the ocean floor by several times.







2. The Moon - been there, done that?

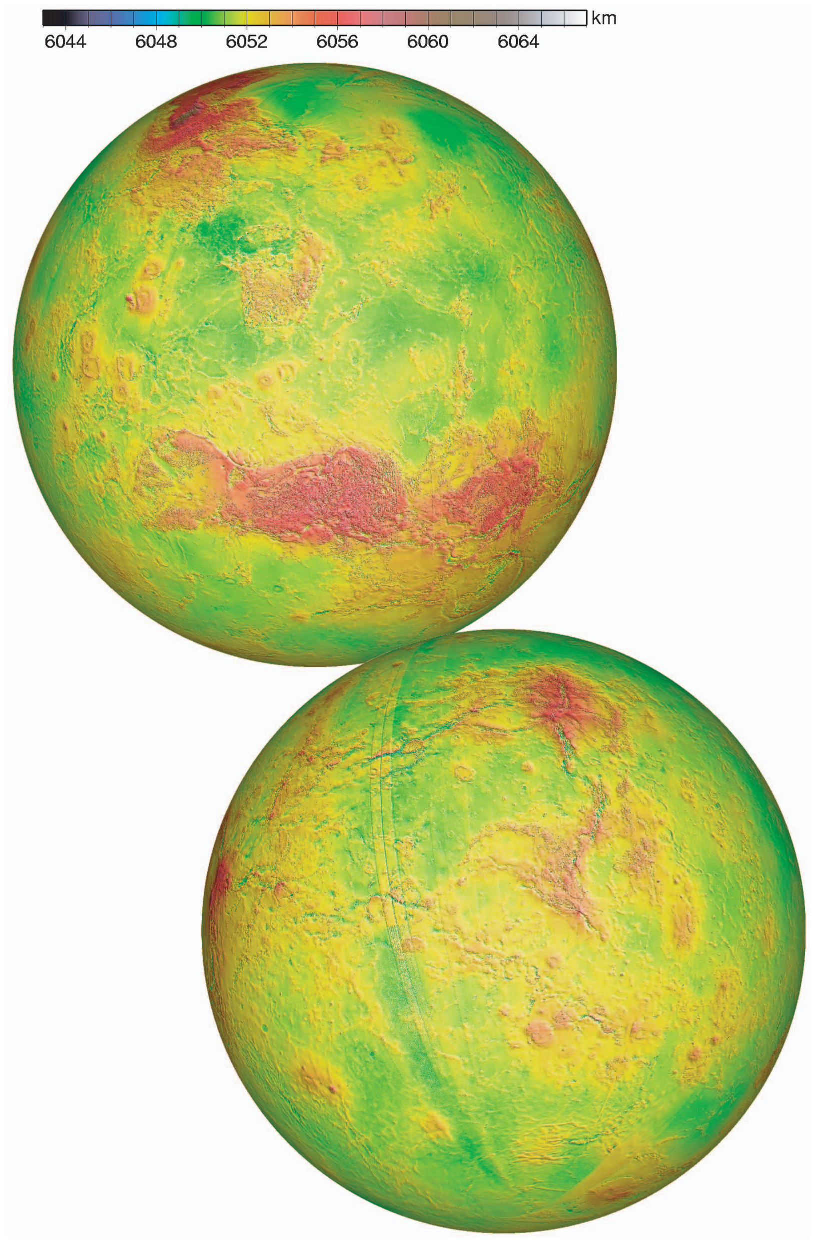
The Clementine Laser Rangefinder provided 72,000+ ranges to the lunar surface during its two-month nominal mission. These ranges, with accuracy of 100 m and cross-track spacing of 80 km, provided the first global shape of the Moon in a center-of-mass frame. Instrument pointing was not known to better than a few tenths of a degree, leading to systematic errors in position of many km. Coverage was not sufficient to supply a shaded-relief image; instead, the mosaiced images from the Apollo Orbiter Cameras have been used to provide contrast.

A scanning lidar system, such as the LVIS instrument flown from aircraft (Blair et al. 2001) or a micro-altimeter with single photon detection (Degnan, 2002) could conceivably provide a map with 5-25 m resolution and cm-level vertical accuracy in the course of a year-long mapping mission. Tracking availability and telemetry bandwidth would pose greater challenges than laser power and longevity.

3. Laser altimetry vs. radar

While Venus will never be measured with a laser altimeter, its shape was fairly well determined by the Magellan radar altimeter, whose footprints varied from 12 to 27 km in crosstrack dimension. The topographic range is about 14 km, relatively benign by comparison with Eros (15 km), Moon (16 km), Earth (19 km), and Mars (29.5 km). Mercury is largely unknown, but the northern hemisphere will be ranged by the Mercury Laser Altimeter on the MESSENGER mission.

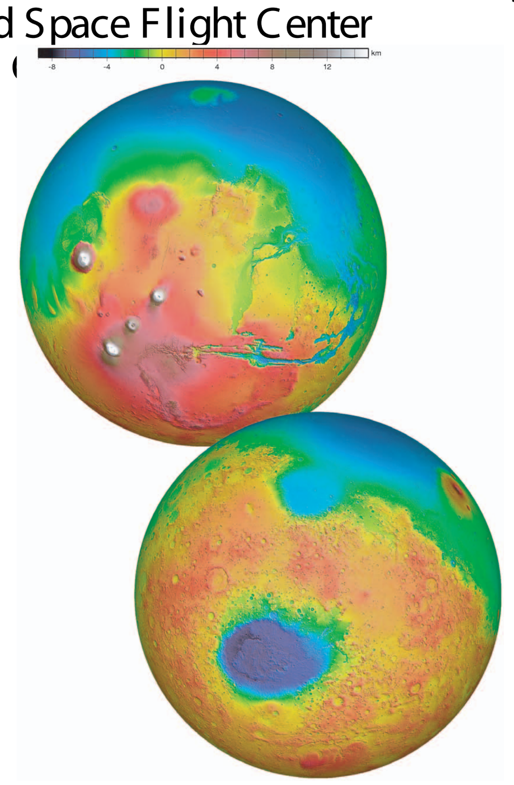
Earth's subaerial topography is accessible to both radar and lasers, but precise global measurements at decimeter scales await the launch of the Geoscience Laser Altimeter (GLAS) aboard the ICESAT mission later this month. This multi-year mission will provide a global cartographic reference frame at an exact-repeat spacing of ~10 km, with 70-m footprints spaced 175 m apart.



4. The IAU2000 cartographic model for Mars

The topography of Mars is measured by the Mars Orbiter Laser Altimeter with an accuracy of about 1 m and 100 m horizontally, limited by the 0.4 m ranging accuracy, the 150 m footprint size of the laser, and pointing uncertainty. Orbit determination using refined force and potential models exhibits sub-meter position reproducibility. The abundant altimetric crossovers in the 93¡ inclination polar orbit allows the pointing to be refined via least-squares adjustment. An iterative solution using 75 million crossovers and 1 million model parameters reveals systematic errors in pointing knowledge near the poles. After adjustment, the pointing is accurate enough to image the polar layered terrains at footprint scale, about 150 m per pixel.

Cartography on Mars is defined by the IAU2000 pole and rotation model. This model is constrained by Viking and Pathfinder Lander tracking, MOLA altimetry, and imaging of the Airy-0 crater landmark by MOC. Total position uncertainty of Airy-0 is 55 m in body-fixed coordinates.



Center of Airy-0 is MOC line 5498, sample 281 (4x summed) - M. Caplinger, MSSS, 2/21/01
Raw sample is 1124 at ET 2001 Jan 31 13:56:21686
Nearest MOLA shot is at 13:56:21671 - 359.7551¡ E, -5.0855¡ N, -2360.3 m at 387400 meter range
MOLA track is sample 1536 (Ivanov) or 1560 (Caplinger) or 1574 (Anderson) - 412 - 450 pixels
MOC pixel is 0.0076794487 radians per 2048 pixels times 387400. = 1.45264 m
At equator, 59.2714 m = .001¡
Offset is 598.5 m (Ivanov), 633 m (Caplinger), 654 m (Anderson): 0.0101¡ - 0.0110¡
IAU1991 longitude of Airy-0 is 0.016¡ East of MOLA - 359.9657¡ E
Difference from 0 is 0.233¡, so W0 should move from 176.868 to 176.6337¡
17.630¡ adopted by IAU.
Uncertainties:

timing:	40 m
MOLA:	15 m
MOC:	15 m
Offset:	30 m
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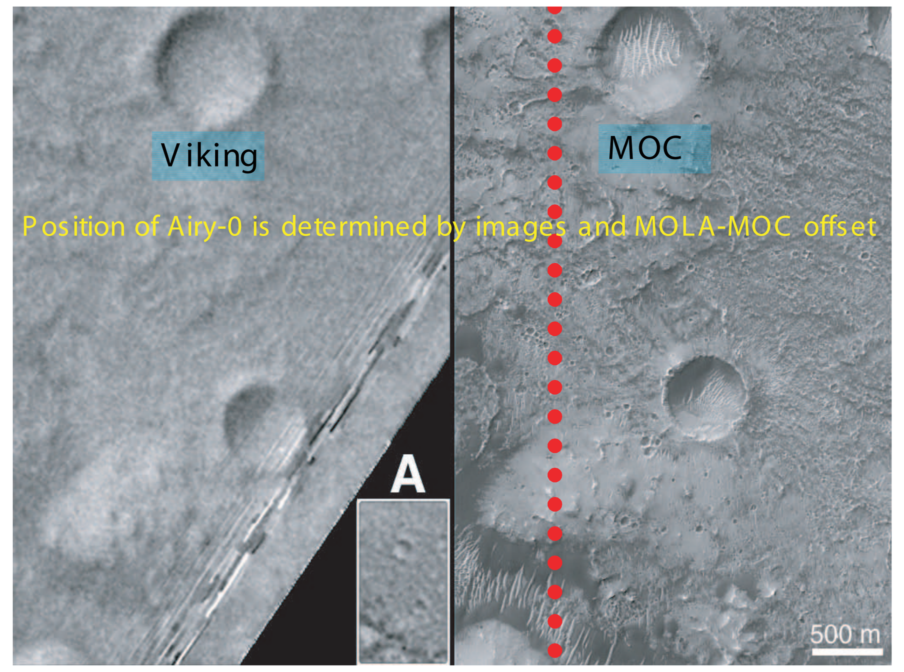
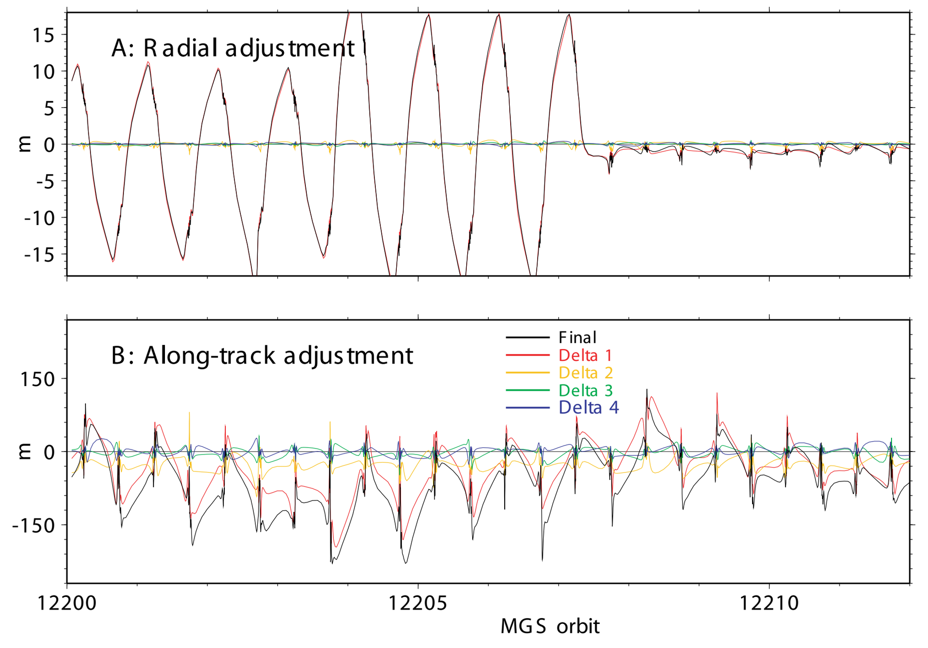
RSS	55 m

MGCWG
April 18, 2001



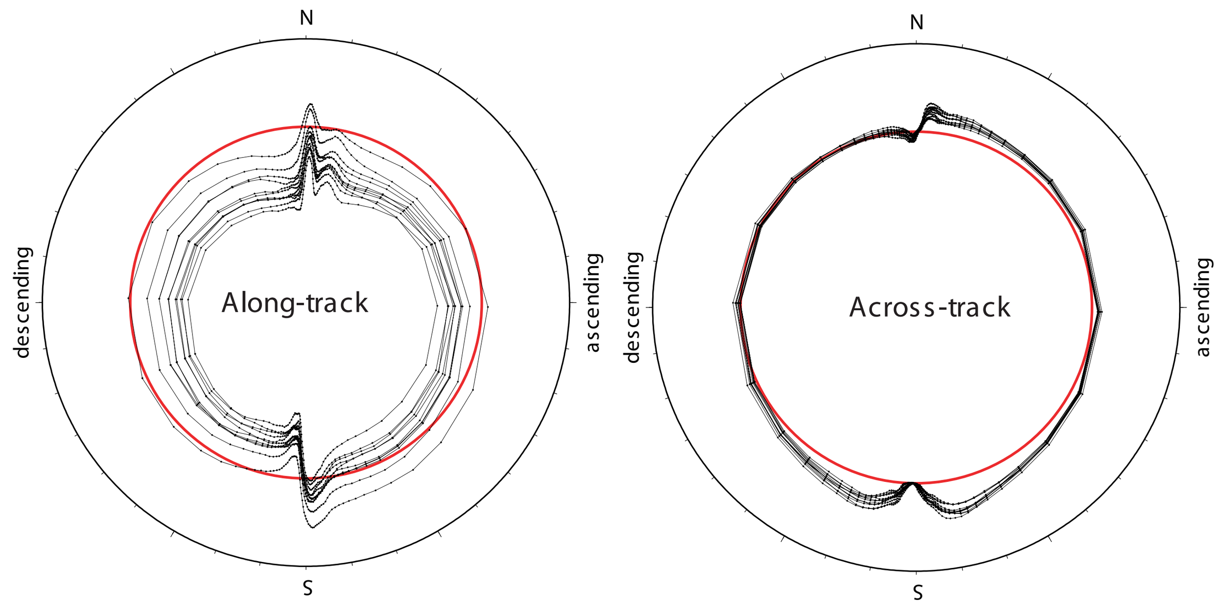
5. Improvements in position accuracy of MOLA tracks

Radial crossover adjustments converge rapidly, within 1 or 2 iterations. Figure A shows initial adjustment (red), final (black), and intermediate steps 2 and 3. Along-track adjustment (B) converges more slowly, eventually changing less than 30 m. Size of adjustment is a quality indicator of pointing knowledge. Across-track adjustments (not shown) also converge slowly.



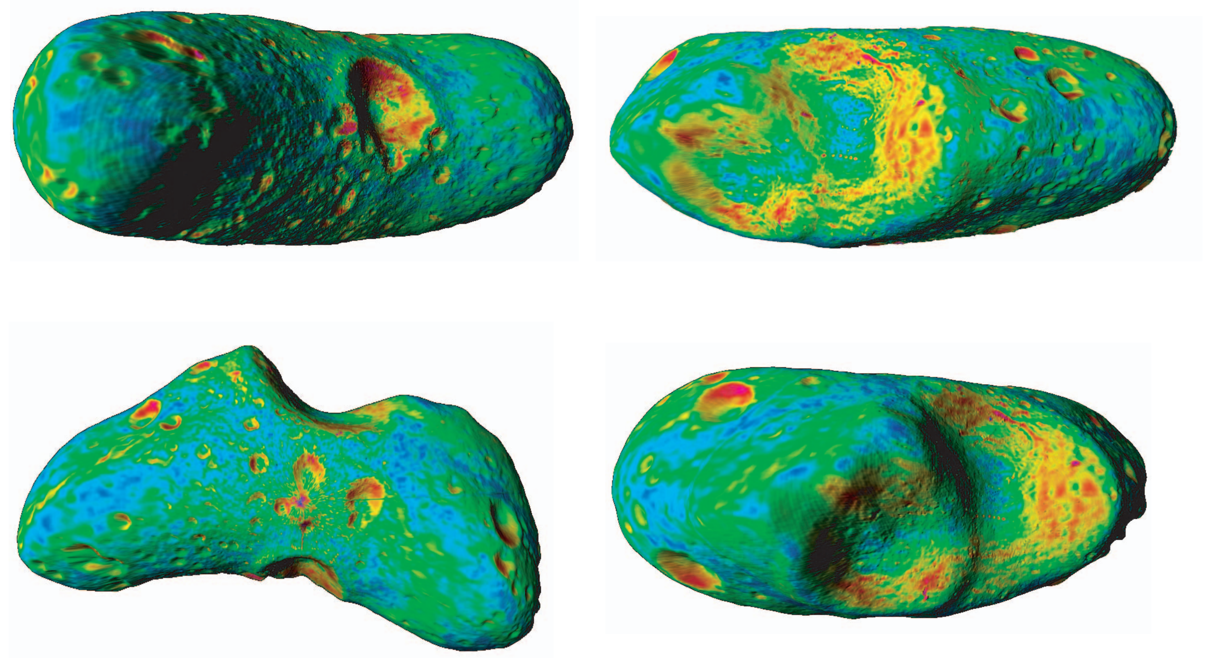
Initial crossover adjustments were performed for one and two cycles per orbit (rev). The polar regions were not well resolved, in spite of a high concentration of crossovers at the poles. In our current adjustment scheme, parameters are distributed according to crossover density.

Pointing knowledge systematically deviates from truth at both poles. The polar plots show average adjustments per day as a function of latitude, with a full scale (radius of red circle) equal to 360 m.

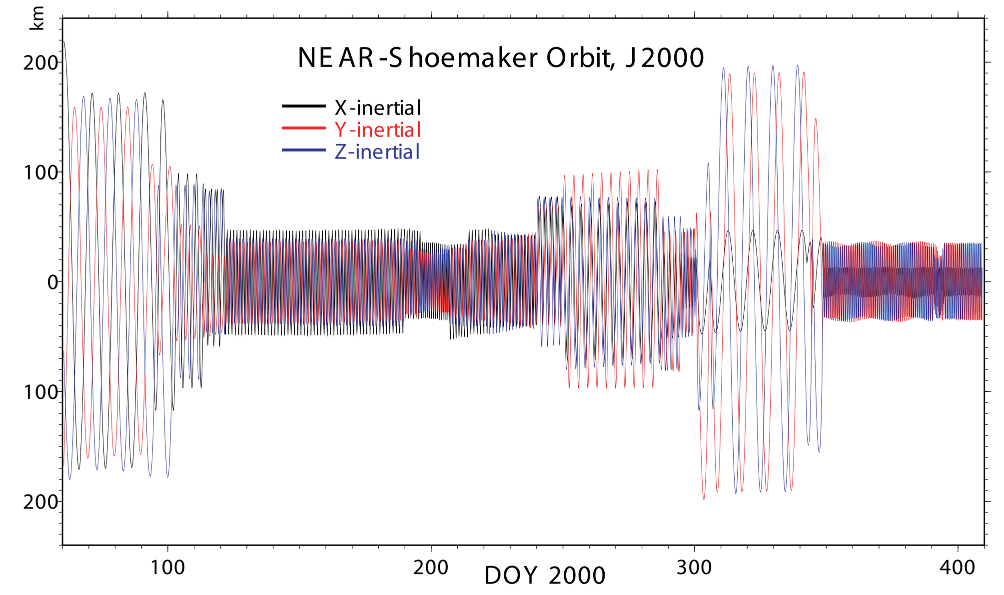


6. Accuracy of the NLR shape model for asteroid 433 Eros

Images of 433 Eros courtesy of the Scientific Visualisation Studio, NASA-GSFC, shaded using the geopotential slope. The NEAR Laser Rangefinder had a footprint of a few meters and ranging accuracy of 6 m over steep slopes, but the absolute position of each range in inertial space is limited by orbital knowledge to about 100 m. The NLR Science Team employed least-squares crossover adjustments to reduce the uncertainty to about 20 m after orbit determination. Progress in improving the cartographic accuracy of the NLR shape model will require incorporation of imaging constraints as well as stronger weighting of altimetry in the orbit determination process.



Orbital phases of the NEAR mission with periapse radii from 200 to 25 km over the course of one year. The mass of the ~33 km diameter asteroid did not provide a strong dynamical constraint on the spacecraft orbit. Navigation relied upon optical determinations after each orbital correction maneuver to constrain orbital elements as the spacecraft maintained a sun-tracking attitude. The NLR instrument was able to range out to the limb at ranges of 200 km or less, providing tracks on both illuminated and shaded hemispheres. The 5-hour rotation period of the asteroid meant constantly changing illumination conditions for the imagers.



Analysis of the orbit determinations produced by the Navigation/Radio Science Team (RS) and the NLR Geophysics Investigation Team (NLR) using a crossover adjustment scheme in the J2000 inertial coordinate frame. The rotation kernel of Konopliv et al. (2002) is used to compare tracks crossing on the surface of Eros. It is apparent that neither optical navigation nor altimetry alone in conjunction with radio tracking suffices to determine spacecraft position to the level of accuracy attainable by NLR. Landmark tracking employed by RS appears to give better results than weakly weighted altimetry, except for the final two months. A combined solution using images and altimetric crossover data types is underway at Goddard.

Orbital Error from NLR Crossovers